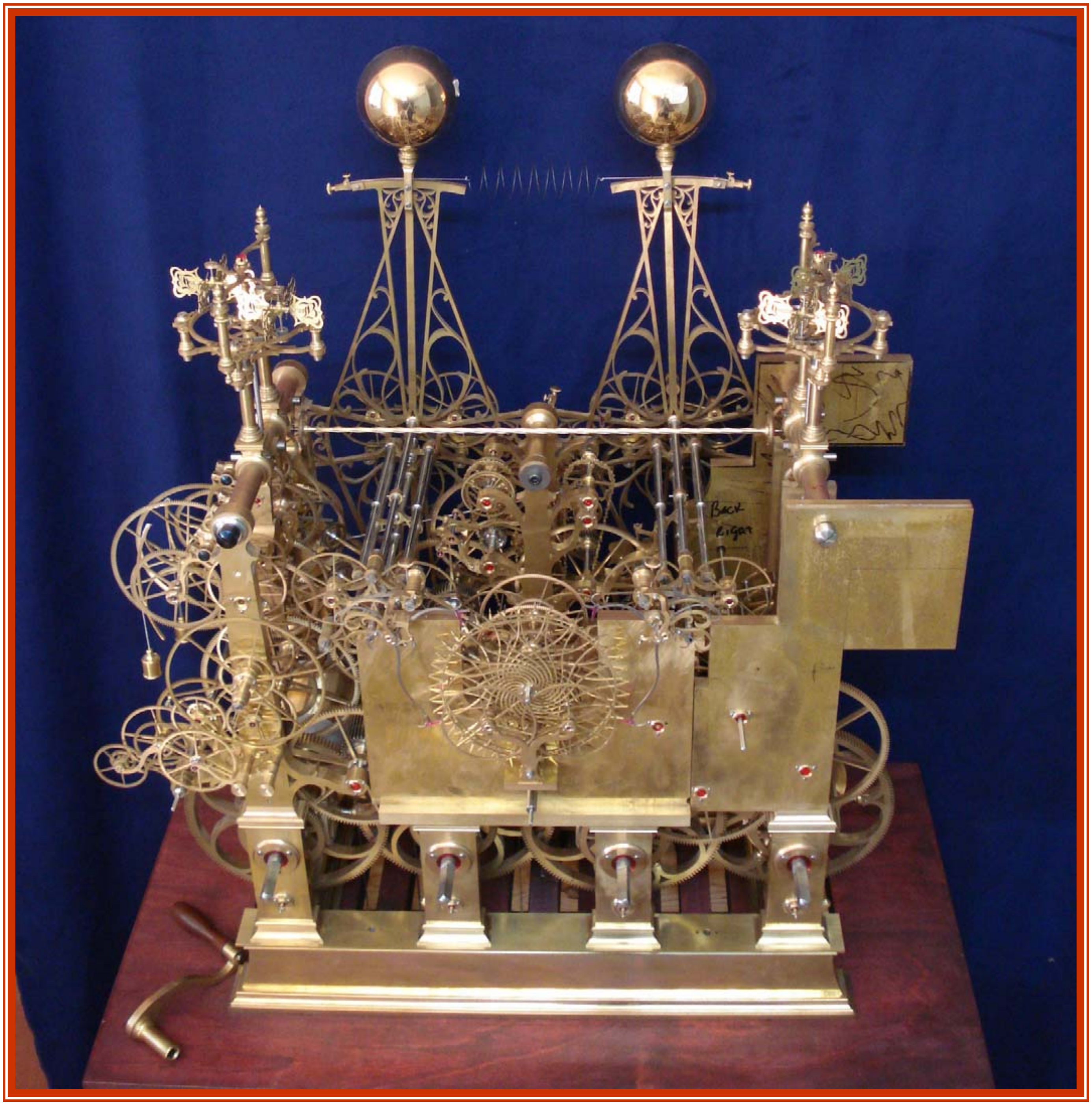
Half Way Point For The Astronomical Skeleton Clock

Where we stand after the third year of construction



Half Way Point For The Astronomical Skeleton Clock

In August 2007 a rear cover article was published in the NAWCC Bulletin outlining an astronomical skeleton clock I designed and am having built by the specialty clock firm, Buchanan, of Australia.[1] At the time there were photos of the full-scale wooden mockup and a description of the various complications based on my website paper.[2] Actual fabrication had just begun the month before.

The three guiding principles I had outlined at the beginning of this project was for the clock to have ***size***, that is it must be larger than a typical domestic clock, but not so large as to be uncomfortable in a domestic setting. ***Complexity***, as demonstrated in a multiplicity of functions resulting in a large number of components, and ***movement***. The last goal is where I believe this clock will excel beyond most others through its use of multiple remontoire,[3] compound fly fans and an escapement with a strong visual impact. Most other clocks even those with many complications; excepting their pendulum and escapement, are still quite static devices. This machine is designed to catch, hold and mesmerize the viewer the moment he or she enters the room though the use of complicated movements in a variety of places and at relatively rapid intervals; combined with highly polished moving surfaces and a touch of whimsy here and there. A sort of Rube Goldberg [4] meets John Harrison.[5]

I knew at the time I conferred with the Buchanan firm that I had found perhaps the only person who had the skills not only to carry out my dream project, but was brave enough to try! I decided right then that I would throw everything at this in terms of specifications and financing. There would be no compromises. I am privileged to be at the point where I was able to meet this gifted man and have the wherewithal to support a multi-year endeavor. When completed we will have about 350 wheels and from 8000 to 9000 parts.

The project began with my conceptual drawings in October of 2003 and continued refinement though the first half of 2005 while Buchanan was working on another large project (Figure 1). During this time the firm had also done some initial design work for a few of the various sub systems I had envisioned for the movement (Figure 2). The initial full scale wooden mockup was delivered July 2006 (Figure 6, page 4) and fabrication commenced in August 2007.

Since then steady progress has been made towards completion. As of this writing, August 2010, I can say we are at or slightly past the half-way point in the creation of this fantasy machine. It's been three years since metal

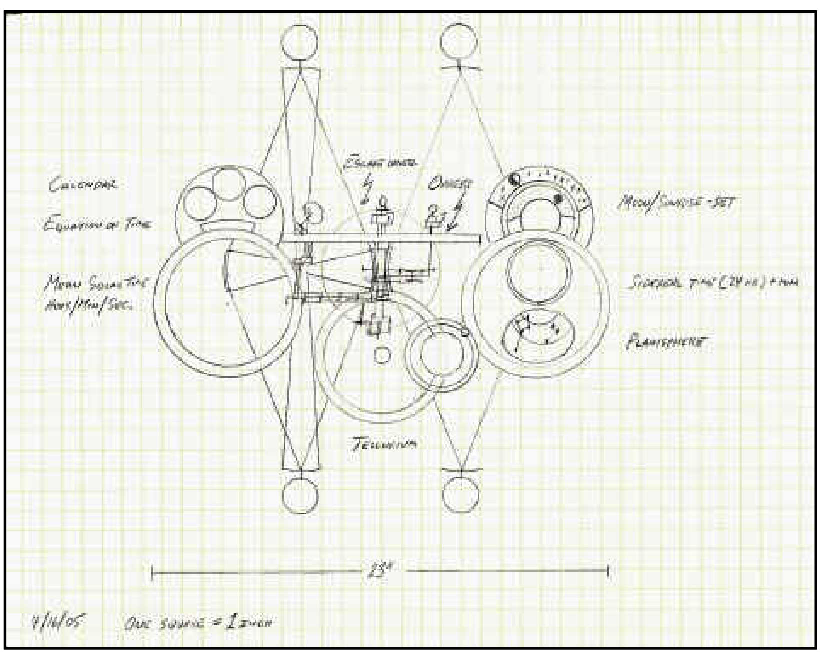


Figure 1. One of the author's later stage conceptual drawings.

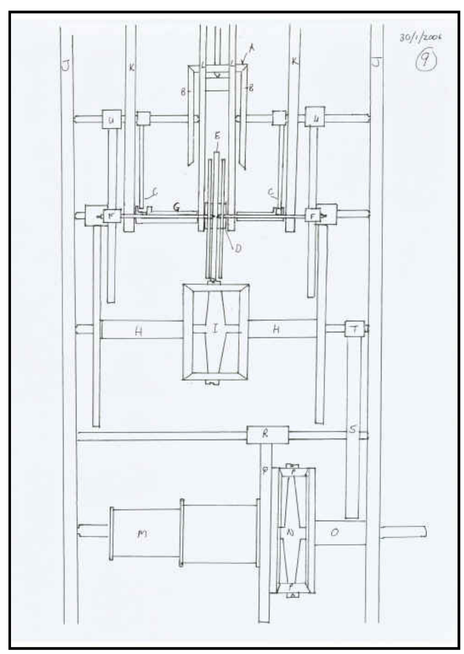


Figure 2. Buchanan's remontoire drawing.

began to be cut, and if momentum is kept and considering our path along the learning curve of this project, we should be finished in another two to two and one-half years making this a decade long endeavor. However, if one looks back in horological history and explores the time frames needed for other outstanding, complicated projects, this is not unusual. A few examples to illustrate.

The medieval astronomical table clock by Eberhard Baldewein, Germany, 1563-1568, for the Duke August of Saxony.[6] A complex institutional sized orrery with clock by Johann Georg Nestfell, Germany, 1757-1763, Vienna, Austria.[7] The Chef-d'Oeuvre (masterpiece) astronomical pedestal clock made by Antide Janvier, France, 1789-1801.[8, 9] More recently: The astronomical skeleton clock by Paul Pouvillon, Nogent sur Ois, France, 1931-1939.[10] The institutional sized World Clock by Jens Olsen, Denmark, 1944-1955 which may have taken a bit longer due to the early death of Mr. Olsen and exigencies of WW II.[11] The Graves super complication watch, Patek Philippe, Geneva, Switzerland, 1928-1933.[12] The Rasmus Sornes clock, Norway, 1958-1966,[13] and most recently, the Türler clock in Zürich, Switzerland, 1986-1995,[14] were all executed over a number of years. But, with the exception of the Pouvillon and Sornes clocks all of these other examples were the product of more than one person. While the lead namesake may have designed and had built fantastic clocks for their clients, these were never made *solely* by their hand. They had subcontracted many of the components out to other artisans or had them built by their own employees in-house. The Sornes clock is exceptional and which in all fairness, far surpasses mine and most other prior clocks in not just complexity but the sheer will of an individual's effort. At the same time, all of those clocks were designed first and foremost to be functional; to convey information and then be to interesting or beautiful to look at. But never were they meant to be whimsically entertaining or just plain fun. And still they are all static machines.

This clock, unlike many of the complex clocks made in the past 200 years will be nearly 100% the creation of one man. The only exceptions, at this point, will be the fabrication of the porcelain dials, roller and jeweled pivot bearings. Even the final gold plating will be done by the same man who created this device. And unlike the more recent efforts in the twentieth century as exemplified by the Olsen and Türler clocks, this project is being made more in keeping with the masters of the 18th century than of those of today. There are no design-to-build sets of drawings. No computer aided design, no computer aided manufacturing. Free-hand drawings with associated calculations are made 'on the fly' as needed just prior to the fabrication of a part or assembly. An examination of Breguet's workshop notebooks illustrate this approach.[15] All of the necessary information to create the device is in the builder's head and guided by the mockup, ad hoc drawings, calculations and with my input for the over arching visual design and functionalities. The entire flat and wheel stock is cut out by hand on a jewelers saw equipped with a magnifying stereoscope (Figure 3). Well over 300 hundred wheels, nearly 2000 spokes, will all be cut in this way. We have finished just over 140 wheels.

Figure 3. Jeweler's saw with binoculars to hand cut all flat stock

Originally the movement was to follow the general design of a conventional plate and spacer frame (Figure 4 and 5, next page). There being two main plates between which the movement wheels would be mounted as well as any sub plates with their components. The raw brass stock for each plate was two by three feet by ½" thick and about 100 lb each. This type of design would present many difficulties for construction as the plates were bulky, heavy and would be difficult to maneuver during the scores of assembly / disassembly cycles. Also, until fully fretted out would be quite opaque making it difficult to see and document what was going on. We immediately saw the advantages of making a temporary set of three pairs of sub plates out of clear ½" clear plastic to solve these

issues. As construction progressed through 2008, the wheels, particularly those of the time train, which was the first train to be made, were filling in the plastic plates nicely (Figure 15, page 8). I became concerned that no matter how well we fretted out the main, metal plates we would lose much of the view of the wheel works within. With the main plates being ½" thick and these frames needing to support over 350 lb in combined movement and drive weights, there was a limit as to how fine one could fret out these plates.

Figure 4. Original plate and spacer configuration

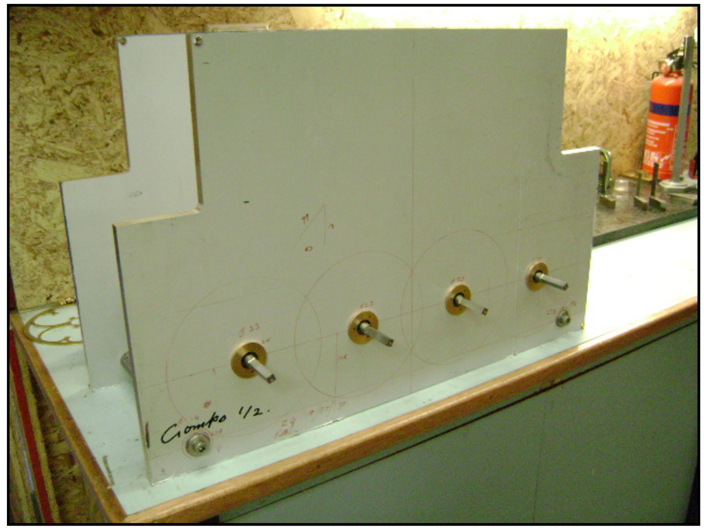


Figure 5. Opaque nature of this configuration.

In most skeleton clocks it is the frame that is paramount, just look at any Smith of Clerkenwell [16] three train musical exhibition clock, or the elegantly curvilinear James Condliff [17] clocks or the beautifully executed Arabesque double frame by Evans of Handsworth.[18] The main show is the frame. This makes sense since most conventional clocks have three to five wheels per train and so it is difficult to make a real statement with only these few wheels to work with. The French make an exception to this with their great wheel skeleton clocks featuring all manner of artistic spoke design within a spare Y-shaped or glass backed frame.

Figure 6. Original plate and spacer frame design, mockup.

In this movement, the attention grabber is the number, style and placement of the wheels as well as their frequent movements in connection with the three remontoire and their flies. So in December of 2008 I asked for a redesign of the clock based on a different frame style so as to more fully expose the wheel works. This was risky because we had already been fabricating parts for a year and a half based on a curvilinear approach exemplified by those main plates as well as any other, non wheel components already made (Figure 6). In March of 2009 a new mockup was produced based on a pillar frame. Fortunately, this fit quite well with what was already done and in the opinion of most people who have compared the two designs, an improvement (Figure 7).

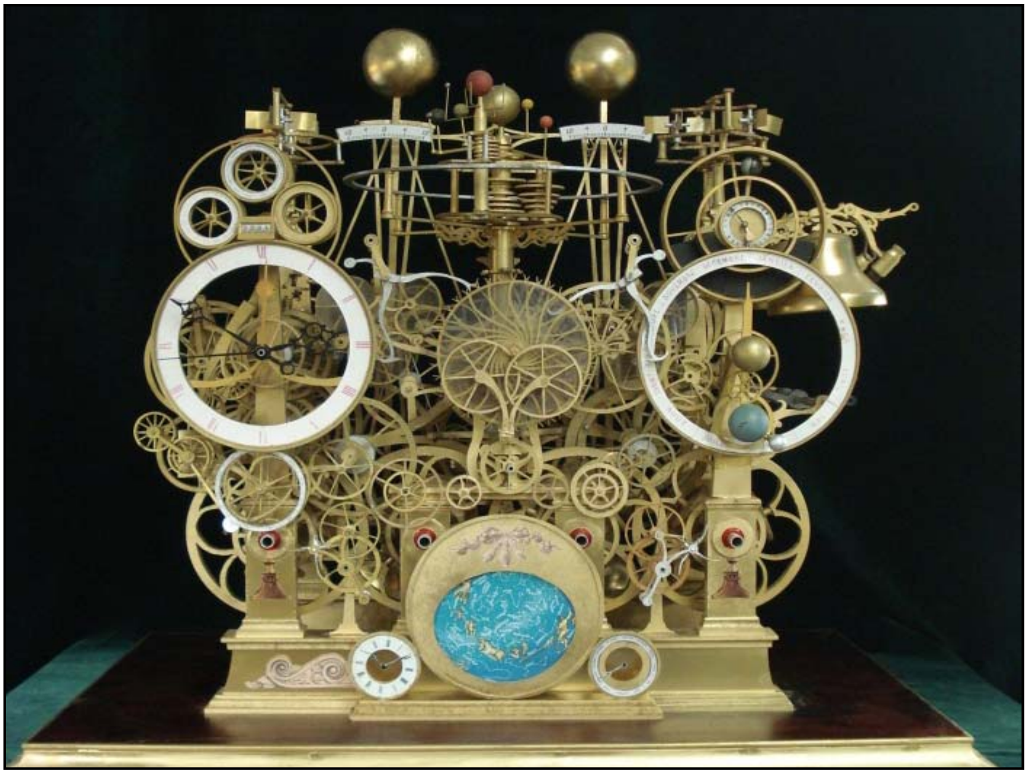


Figure 7. Revised pillar frame design, mockup.

This change has many advantages in addition to allowing more exposure of the movement. It allows for a modular design, with each train being independent from the others for purposes of fabrication, assembly/ disassembly. In reality there are some overlapping functions between the modules but this in no way diminishes the serviceability of the design. We are creating this movement with an eye toward its future maintenance. If, after twenty years or so the movement needed service and it was near impossible to do so, then we'd run the risk of it falling into disrepair and perhaps, ultimately ruin; a scenario that has befallen some significant clocks in the past. To this goal the four corner pillars are separable just above the main train weight barrel pivots and allows one to service the upper time and strike trains without having to deal with the heavy barrel and base frame components. The four lower center pillars support interior sub plates containing the celestial train remontoire, the time train escapement and support for the orrery superstructure. These plates can be removed as a unit (figure 38, page 14). With this minimalist frame we have also created in the words of the builder, "a spider's web holding a haze of wheels". One negative aspect to this design is that placement of the wheels is far more restricted; we no longer have a blank canvas in the form of a vast plate from which to choose their locations.

In the original design specifications I had all but the weight barrels running in jeweled pivots with the former in sealed roller bearings due to the stresses put upon these areas. Later this was widened to where all of the long arbors that spanned completely between the front and back pillars, about 13", would also be in roller bearings. Such long, heavy shafts present the risk of cracking the jeweled pivots during the many disassembly operations. We also later determined that all wheels that would turn faster than once per hour would also use them. The two exceptions being the remontoire and strike fly fan assemblies as these areas command special visual attention and real jewel bearings would show best. Those components are located in easily accessible areas for regular service. All of the rest of the wheels, approximately 250 or so, will run in dry, jeweled bearings. Breguet is quoted as saying "Give me the perfect oil and I will give you the perfect watch." referring to the trouble with deterioration and dirt accumulation associated with oil and if it can safely be eliminated altogether, so much the better. Also employed is an escapement based on Harrison's grasshopper design; one which sidesteps the need for oil. We are using hard tool steel for the pivots which are, in turn, embedded into the stainless steel arbors. I will readily admit that we are exploring some new territory here and there is some controversy as to the wisdom of this arrangement. I am confident that we have struck the right balance in the design of the various wheel pivots that will result in a machine that, considering its great complexity, will run as trouble free for as long as can be reasonably expected before major servicing. Wherever we have roller bearings there are custom made red plastic rings and caps to hide the bearings (Figure 8), and match the color of the actual jeweled pivots, (Figure 9).

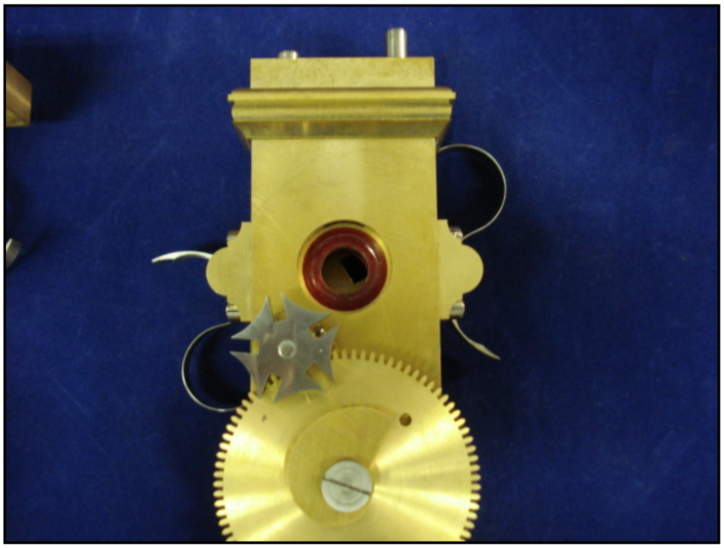


Figure 8. Red plastic ring hides roller bearing pivot.

Figure 9. Typical jeweled bearings in decorative chatons.

Several novel designs are employed in the time train. First being the dual Bernard-Henri Wagner type remontoire [19] driven from a common differential [20] (Figure 46, page 16) and powering a pair of independent, counter rotating grasshopper escape wheels [21] (Figures 20, 21, page 9). The other is the compound pirouette flies for the remontoire (Figures 15, 22, pages 8,10) and the epicyclical maintaining power for all four trains use wheels in two dimensions rather than the usual single plane (Figures 13 and 33, pages 7,12). Before construction could begin working models of these components were created from plastic to test our designs. Indeed a functional model of the entire time train was made all the way through to the dual balances. From this model we were also able to not only test the practicability of the train, but also to redesign and refine how the components within were arranged and mounted relative to each other to achieve the most pleasing visual presentation. One example is where we had a row of six drop-down frames to hold the dual remontoire making this system look cluttered (Figure 10 and 11). We were later were able to reduce this to two (Figure 12, next page).

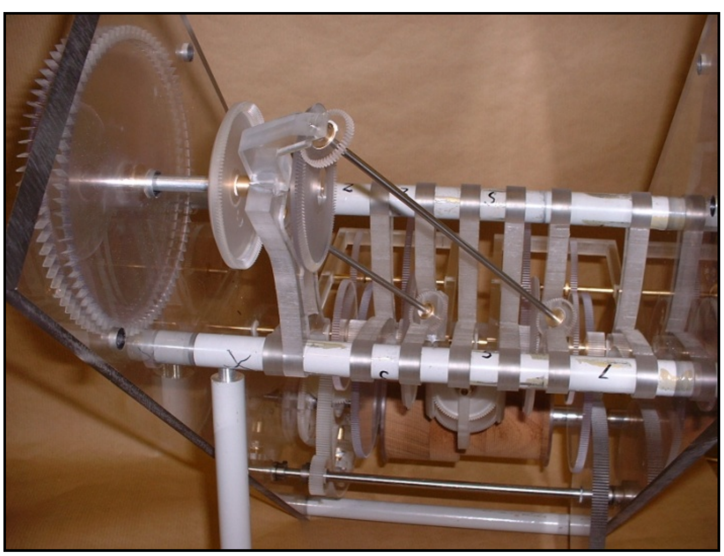


Figure 10. Plastic working mockup of time train, top view.

Figure 11. Plastic working mockup of time train, side view

The sequence of fabrication began from the winding barrels (Figure 13). Each one has epicyclical [20] maintaining power with the planetary gears being set at 90 degrees to the sun wheel for a better view of this system. In addition to the three trains one would expect from a quarter chiming clock a fourth train is used to drive the sixteen celestial functions.[22] Afterward, the first clear plastic sub frame was made to house the build-out of time train (Figure 12).

Figure 12. Fabricated time train with improved design.

Figure 13. Winding barrels showing 90 degree epicyclical gearing.

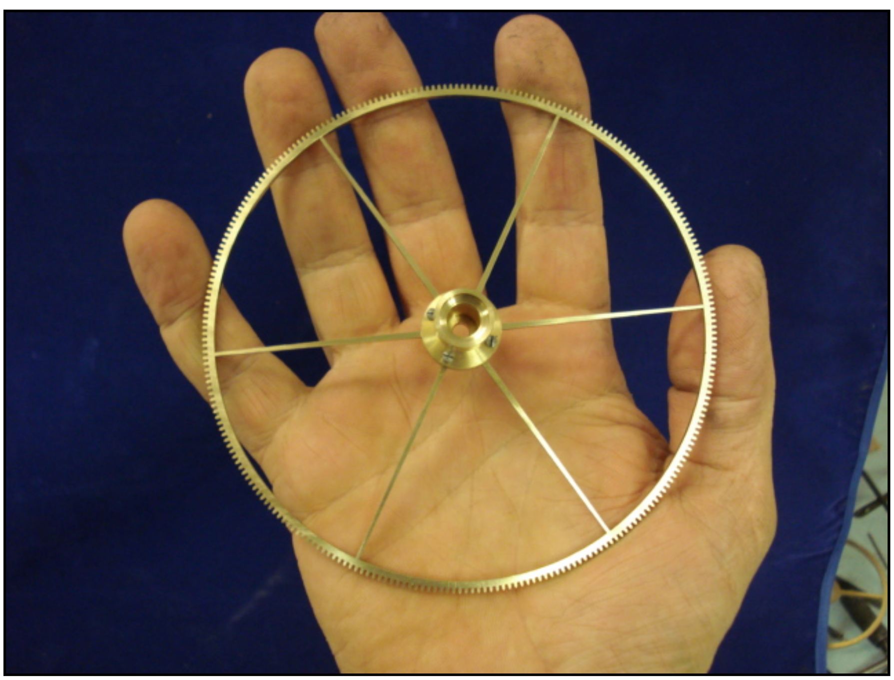


Figure 14. Typical 'feather light' wheel style.

Buchanan's signature wheel style is to cut as delicately as possible with thin spokes and rims; it is the most difficult style of wheel to make as anyone who has ever tried to make such wheels can attest (Figure 14). This not only looks elegant but also shaves mass from the movement, increasing efficiency and lessening friction. In a machine of this size and complexity, friction and mass are our constant enemies.

By September of 2008 the time train, excepting the pendulum balances and grasshopper pallets, was largely complete. Total parts count for the time train, 483 plus 60 wheels, and the pair of remontoire flies, 330 plus 2 wheels (Figures 15). Compare this to Figure 49, pg. 16.

By the end of the year the balances were complete; an additional 432 parts plus 12 antifriction wheels. Each frame is cut from one piece of ¼" stock, 23" in length and takes two weeks to pierce in the jewelers saw. The design is first drawn on contact paper which is then attached to the brass plate and then carefully cut on the jeweler's saw (Figure 16). There can be no errors or the entire part must be scrapped.

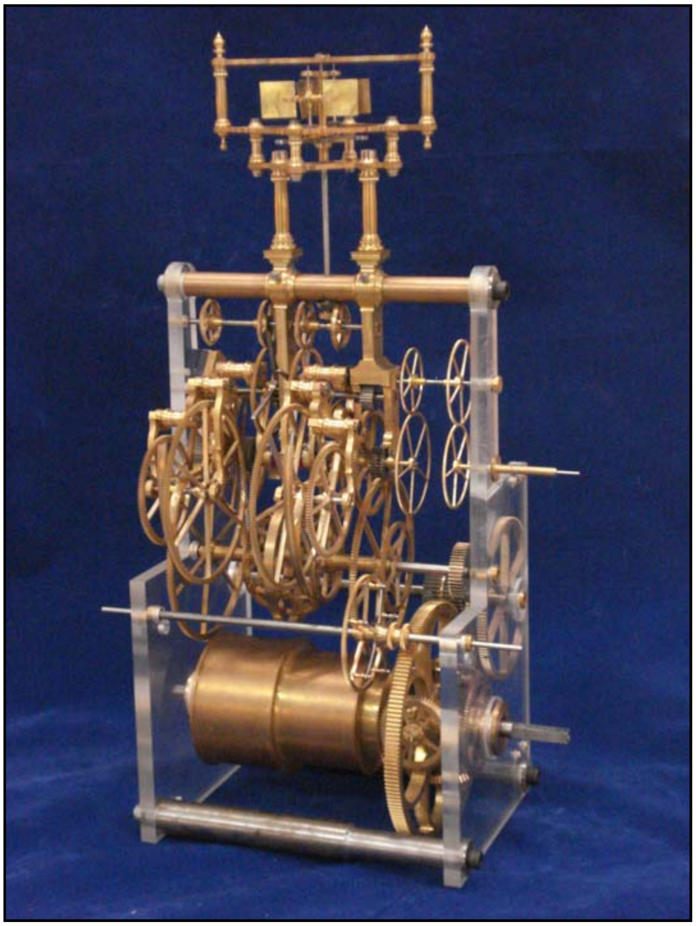


Figure 15. Completed time train between temporary plastic plates.

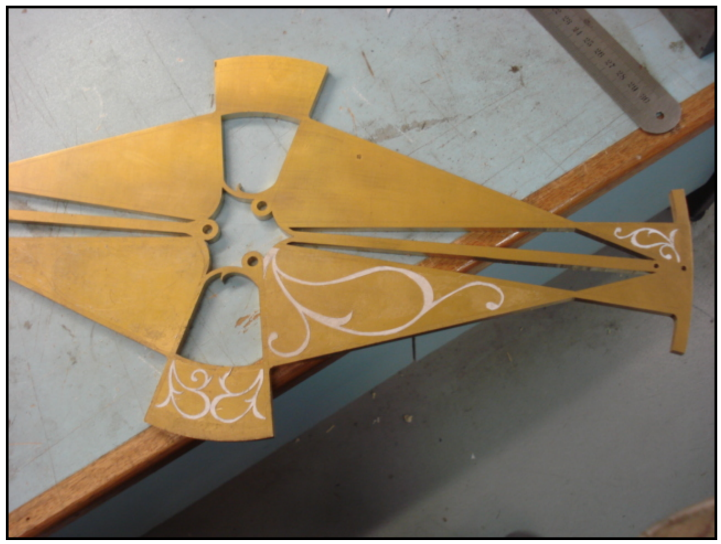


Figure 16. Paper design template applied to the brass blank.

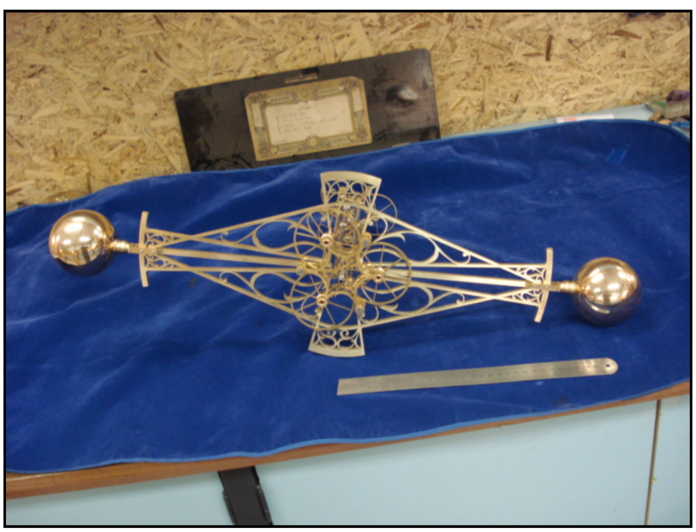


Figure 17. Completed balance, approximately 23" long.

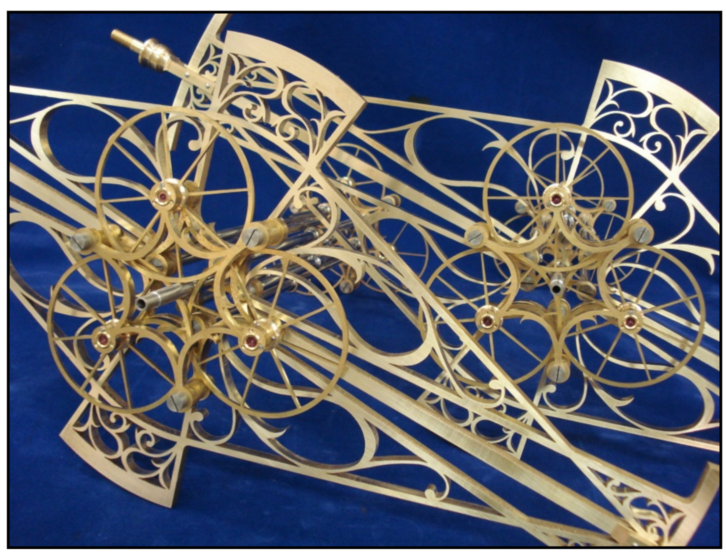


Figure 18. Close up of the intricate balance fret work.

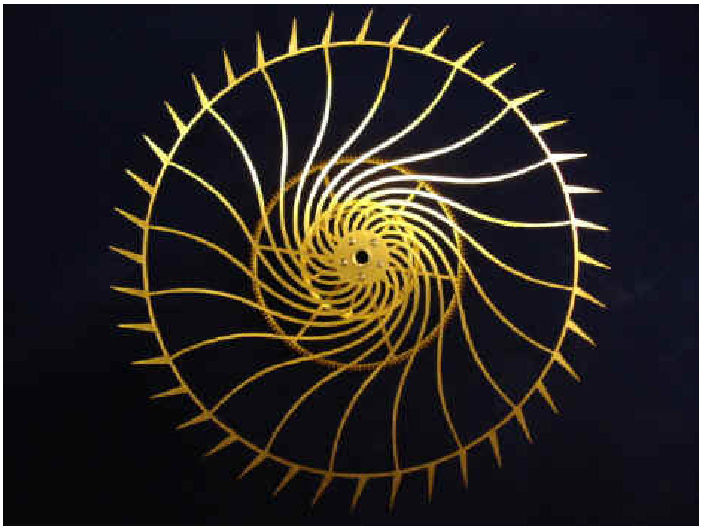


Figure 19. Swirled spoke patter all cut by hand from one piece.

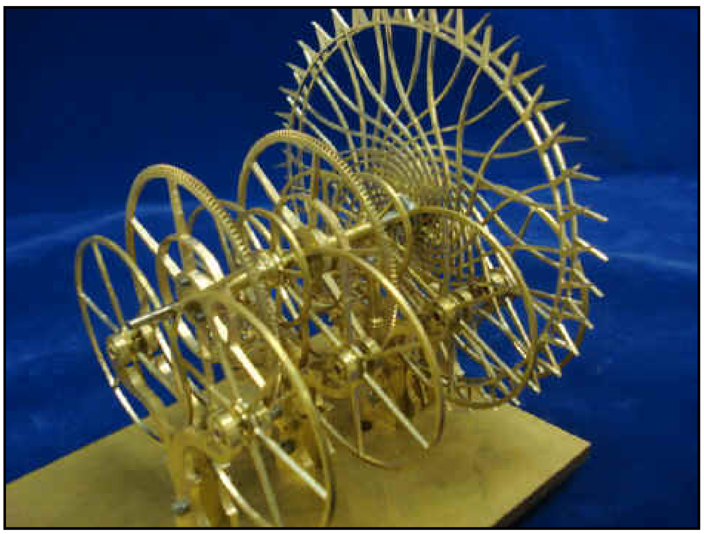


Figure 20. Escape wheels rotate on an antifriction wheel set.

Figure 21. Fanciful escape pallets designed to look like birds.

The two grasshopper escape wheels have a special swirled spoke pattern so that as they rotate past each other in opposite directions one will see a kaleidoscopic effect (Figure 19). These ride in a set of eight antifriction wheels (Figure 20). The grasshopper escape pallets were purposefully made in a fanciful way so that when operational each resemble a pair of birds, complete with jeweled beaks, head with a comb and a flourish of tail feathers in brass and steel 'pecking' at the escape wheel teeth (Figure 21). All of the flat jewelling is made in house. There are 220 parts plus 18 wheels for entire grasshopper escapement assembly (less balances).

By January of 2009 the grasshopper pallets and all other components necessary to complete the time train were finished. The clock was set running for the first time under its own power at 2:30 AM on the 15th – it was alive! The two second swing, at half the speed of Harrison's original H1, was hypnotic.

Our success, however, was short lived. Problems arose with the grasshoppers, too much power was being consumed and tripping was a problem. These had to be completely redesigned and the current components scrapped; a month of work lost! Throughout the rest of the year further refinements were made on the operational characteristics of the time train. The remontoire were interacting in a negative way with the large recoil inherent in Harrison's design. This resulted in their coming to a 'bounce' when reaching their apex and this, combined with more mass within this system than desired, again caused the escapement to trip. Buchanan re-machined the remontoire to shave 34% of the mass as well as a redesign of the cycling stop cam. To the best of my knowledge this type of remontoire has never been tried with a recoil escapement. These issues did not arise in the working plastic model since plastic has far less density than metal.

Concurrently various components such as cocks, bridges, columns, mounts, the remontoire swing cages, fly fan blades and their cages were now ready for their final decorative curvilinear shaping and fretting out, all of which is laborious and time consuming (Figures 22 and 23).

Figure 22. Completed fly with pierced blades, columns and finials.

Figure 23. One of the two time train Wagner remontoire.

In addition, another major subsystem was also completed, the Robin remontoire,[23] which mediates the release of the celestial train at 186 parts, 11 wheels. Another difficulty was experienced in connection with the detent mechanism controlling this remontoire; too much power was needed and thus became unreliable. The novel anchor type assembly was replaced with a simpler rotating detent harkening back to Wagner's design of over 150 years ago. The old masters still have something to teach us! This system occupies much of the rear of the central sub plate (Figure 24 and 25, 47 and 48, page 16).

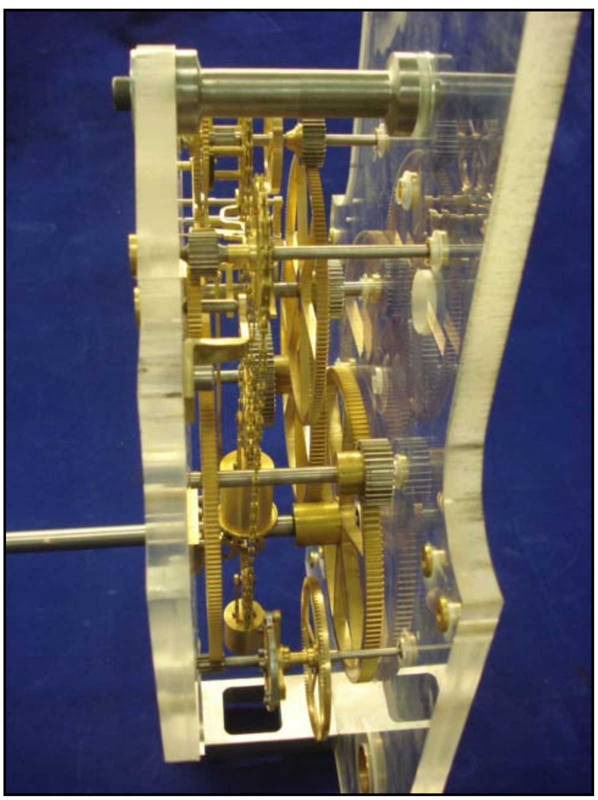


Figure 24. End view of Robin remontoire.

Figure 25. Side view remontoire controlling the celestial train.

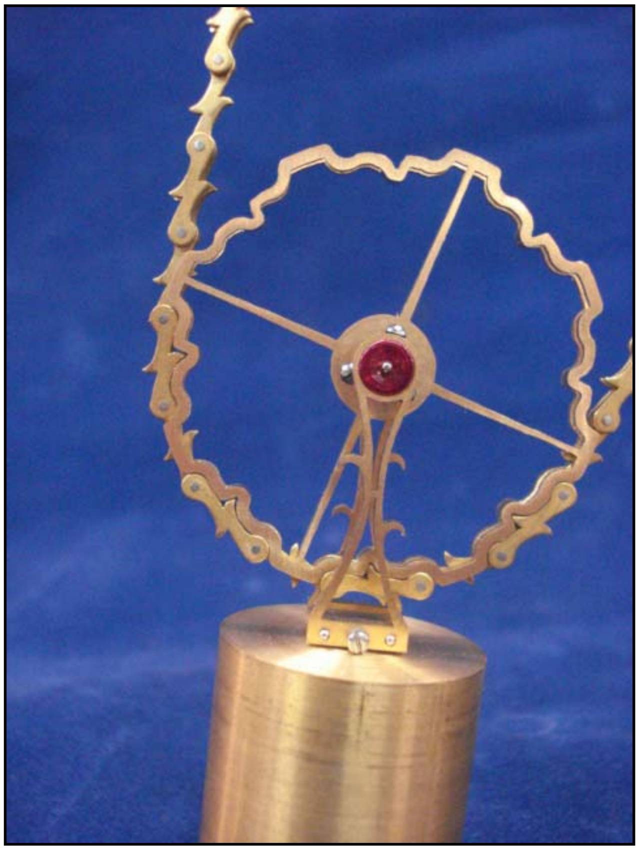


Figure 26. Intricate Robin chain and pulley profile.

The remontoire chain requiring 255 additional parts was a custom design with miniature ivy spurs for each link in keeping with our curvilinear / ivy motif for the movement. These links required an intricate pulley wheel rim design. The pulley weight support is also carefully decorated and fitted with jeweled pivots (Figure 26).

With the Robin remontoire and time train largely complete and some lower wheels for the other three trains finished, work began in September on the main frame components; beginning with the base and lower pillar members. The lower frame and its molding details were first created and refined through several iterations in wood (Figure 27). Once the look was satisfactory, fabrication of the metal stock began (Figure 28). These were completed by December. The long frame members were first heat treated in a special-built furnace to prevent warping under the milling process. Notice the intricate frame molding work. These required custom fly cutters made by the fabricator as well as matching custom female cutter profiles for the inside corner work (Figure 29).

Figure 27. Frame and molding detail fabricated in wood model.

Figure 28. Raw frame stock assembled before final machining.

Figure 29. Decorative molding and sloping side base wall.

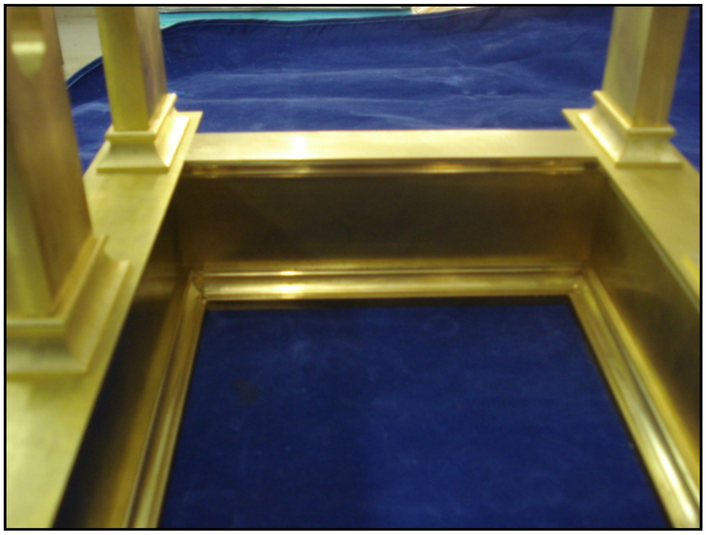


Figure 30. Interior, lower rail decorative work

Even the interior lower rails, something that one would rarely see without difficulty, have decorative molding work (Figure 30). The crowns of the lower pillars

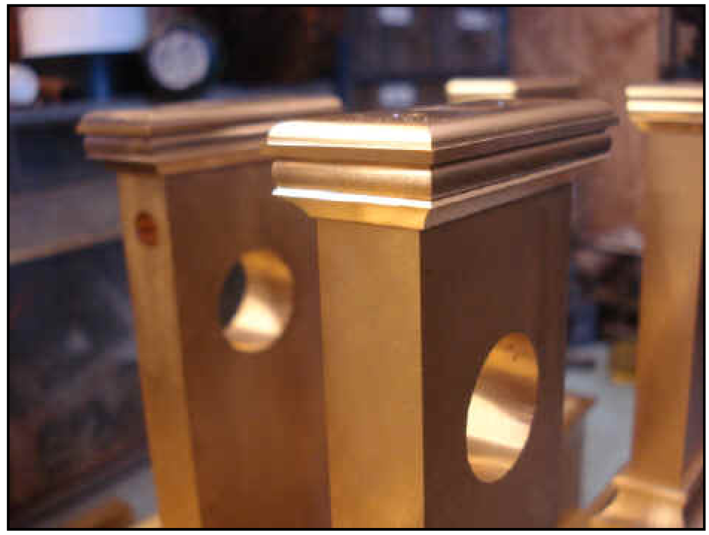


Figure 31. Intricate crowns requiring multiple machining steps.

require five separate steps and fly cutters. As finished as these frame members look, there are still several final embellishments yet to be made to the to the corners of the pillars as well as the polishing and gold plating yet to take place (Figure 31). Figure 32 shows the completed lower movement frame and in Figure 33, the frame with the winding barrels fitted.

I had stated earlier in this article that the attention grabber for this project would be the wheels, rather than the frame as is the case in most conventional skeleton clocks. However, as the reader can now see, we have progressed in our efforts to such an extent that the frame has taken on its own visual importance. No compromises!

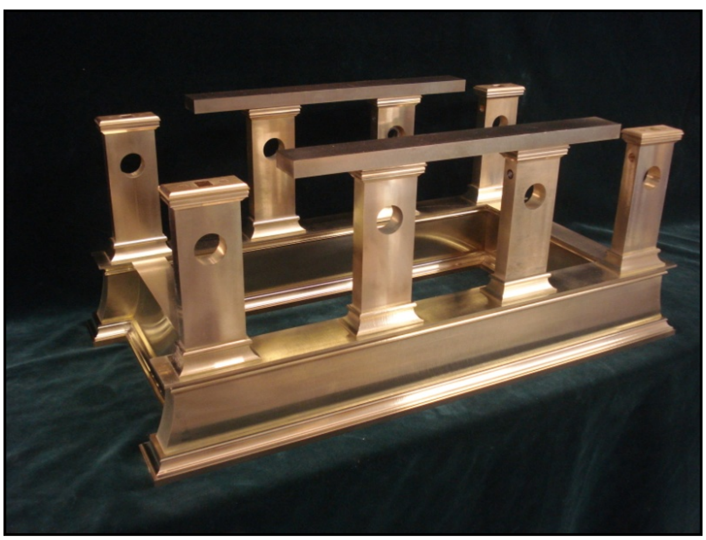


Figure 32. Completed Lower frame assembly.

Figure 33. Lower frame containing winding barrels.

During this time other components were being completed. Just to keep things interesting, the bell hammer actuating cams, like those of the four main winding barrel wheels, have a fancy spoke design (Figures 34 and 35). Total parts excluding the arbor and collets are 135. A conventional design would contain at most 15 to 20 parts with most containing less than a dozen when using a solid cam for the hammer lifters.

Figure 34. Hammer lifting cam components.

Figure 35. Completed quarter and hour strike cam cages.

Figure 36. Last photo of movement housed between the temporary plastic frames.

In December the project was carefully photographed for the front and rear cover shots of the January 2010 Horological Journal. This photo was one of the last to be made with the movement between the temporary plastic frames. It contains the entire working time train, escapement, celestial train's Robin remontoire and parts of the two strike trains. While this photo may look like a large proportion of the movement is complete, it is still lacking all of the sixteen celestial functions comprising again as many components as those already completed.

January 2010 began with the design and fabrication of the upper frame components. This was to be far more involved than those of the lower frames which only had to contain the four main barrel wheels. Now all of the many other wheels, pillars, cocks, and bridges that have up to this point been between the temporary plastic frames had to be transferred to the new rough metal frame plates. There are four corner plates (Figure 37) and a complex center sub plate fitting between the corner plates that will contain the escapement, Robin remontoire, orrery and pendulum supports (Figure 38). The transference of the myriad pivot holes and other mounting positions began in April with the careful disassembly of the plastic plate sections. Since the clock was fully functional up to this point, these plates served as templates for drilling the metal plates (Figure 39). A special jig was made to mount these to a mill that was equipped with a digital plotter, the closest we come to digital machinery here. Each hole center is measured from the temporary bushing left mounted in the plastic (Figure 40).

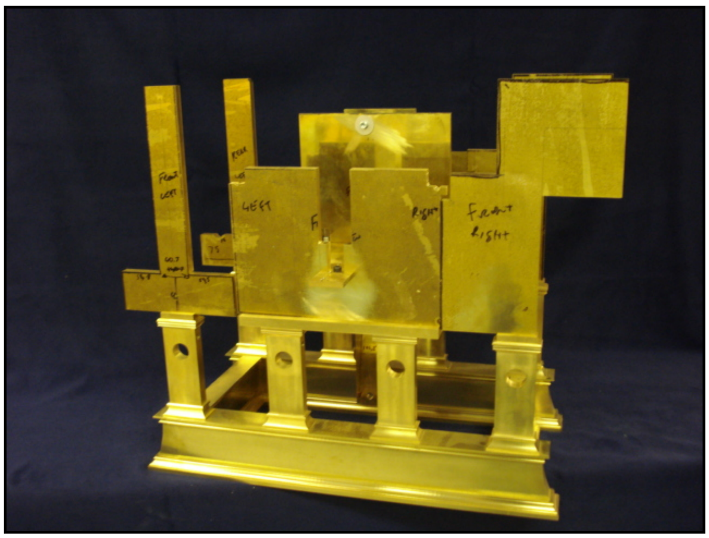


Figure 37. Rough corner and central plates.

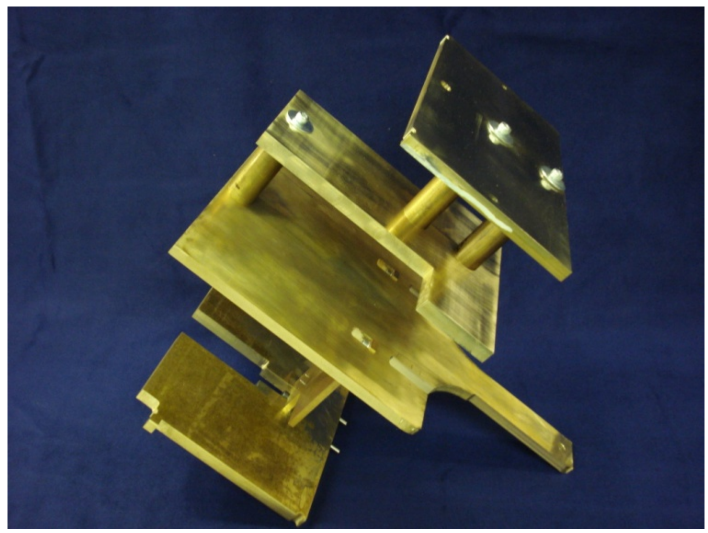


Figure 38. Complex central frame section.

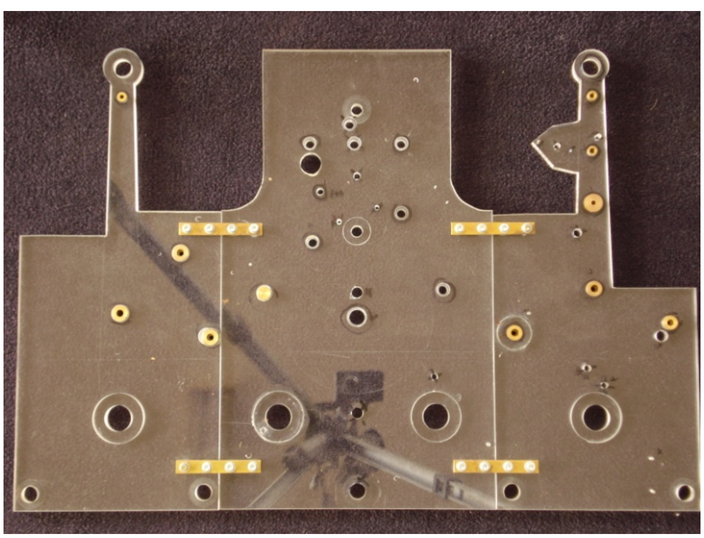


Figure 39. Original plastic rear main plate.

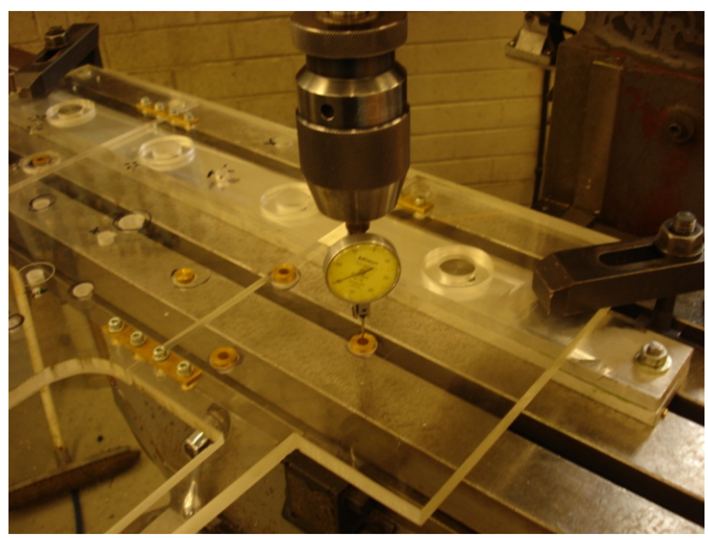


Figure 40. Checking each hole for proper center positioning.

Afterward the measurements are double checked against the plastic plates before drilling begins (Figure 41). Later the pivot chatons are fitted into the plates (Figure 42).

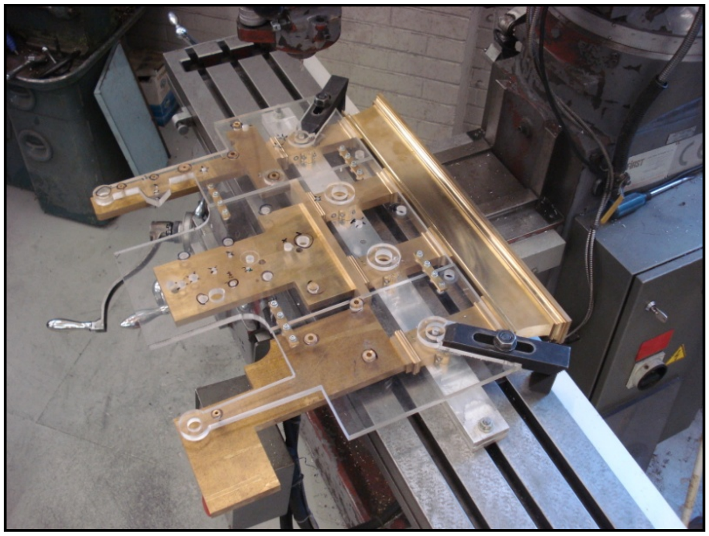


Figure 41. Original plastic frame used as template prep for drilling.

Figure 42. Sixteen chatons inserted into six plates faces.

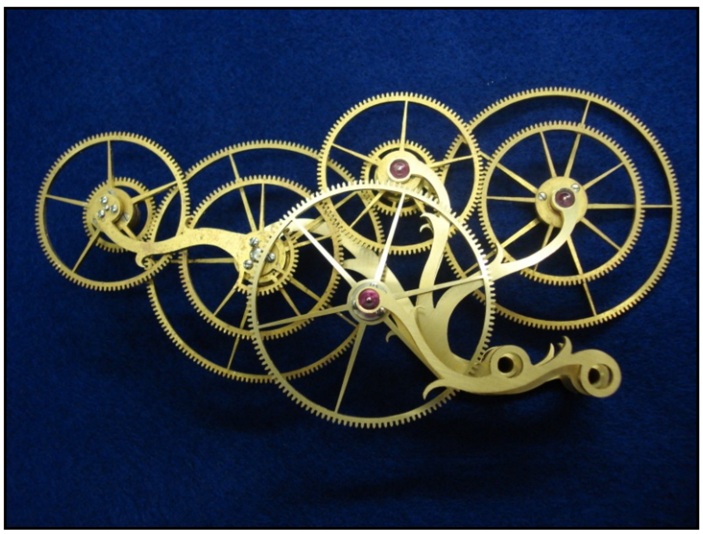


Figure 43. Equation of time differential drive (kidney not shown).

During this time the equation of time drive (Figure 43) and the reserve power indicators (Figure 44) were being made as well as other refinements such as the dishing of the entire medium to large sized pinions and machining decorative collets (Figure 45).

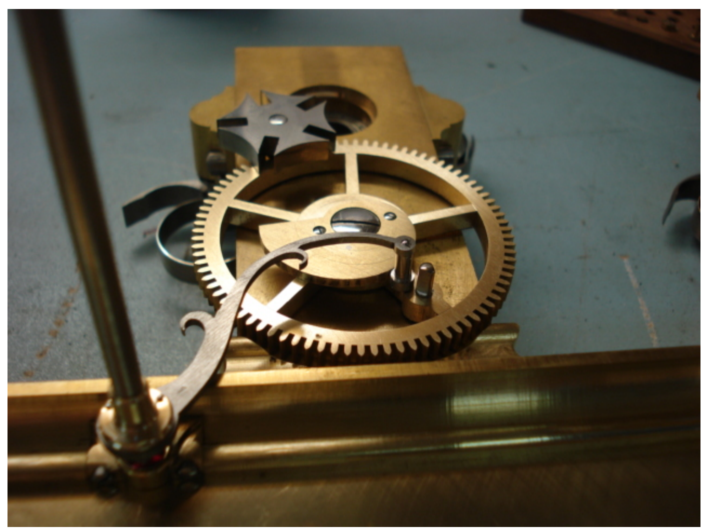


Figure 44. One of four power reserve indicators.

Figure 45. An example of the numerous decorative collets.

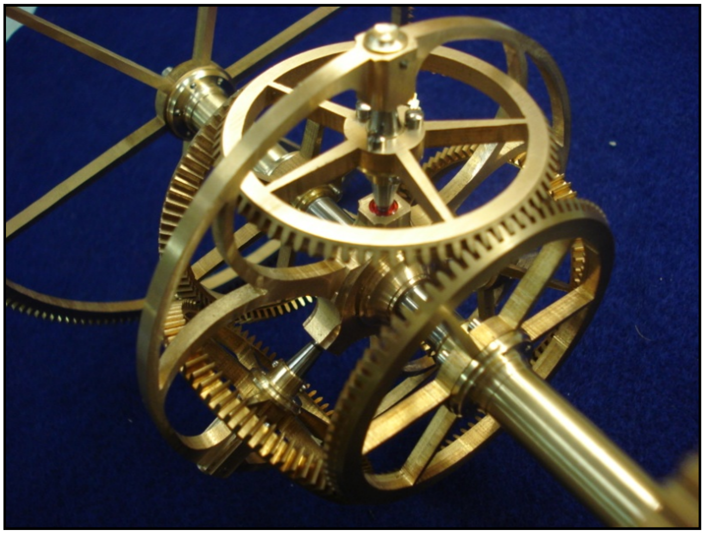


Figure 46. Differential drive for dual time train remontoire.

Other components underwent further machining to add definition and reduce mass; illustrated is the differential drive which will run the Wagner remontoire for the escapements (Figure 46).

By July the upper plates began to take on their organic, 'tree' shape. Remember that each plate is ½" thick and is being cut on the small jewelers saw seen in Figure 3. Many dozens of blades were destroyed during this process. The branches will be gradually thinned out as they rise toward the top, just like in a live plant. The areas that contain the arbor's chatons will remain at ½" since the wheel arbor lengths have all been made (Figure 47 and 48). This however is a bonus as these will be the "red fruit" in the form of the jeweled chatons hanging from the branch ends. Also all of the screws will be polished and heated to an electric blue color. These two color combinations in addition to the silver stainless steel of the arbors and the rose color of the bronze wheels against the gold background of the frames should provide a stunning display. See how the time train wheels literally spill out of corner pillars; allowing for maximal visual impact. A great

Figure 47. Organic 'ivy / trees' comprising the middle frames.

Figure 48. Corner and center tree frames installed in movement.

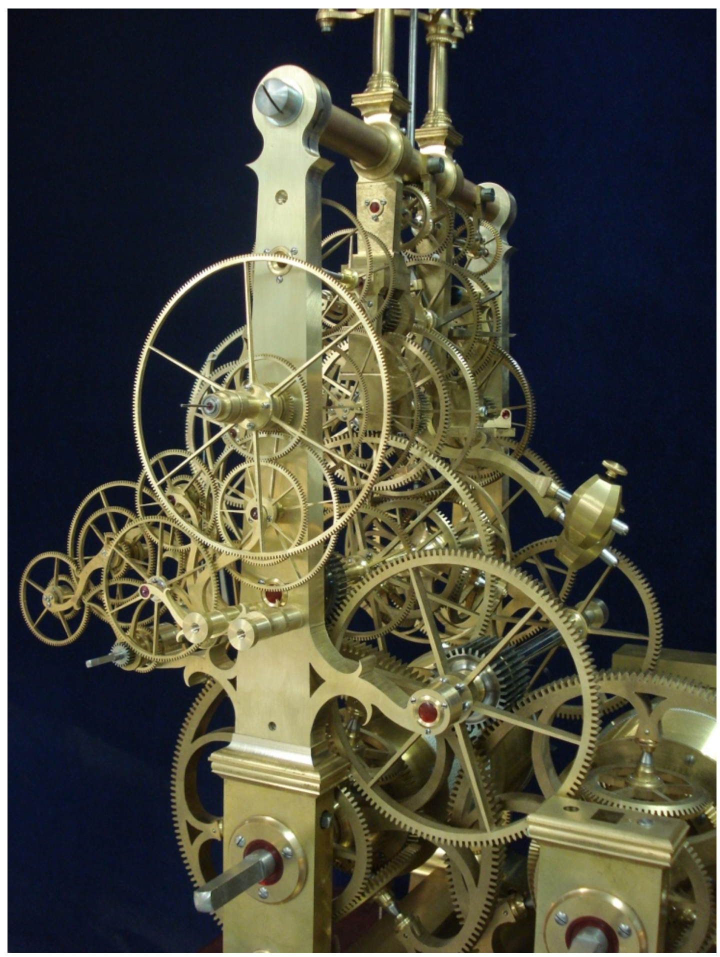
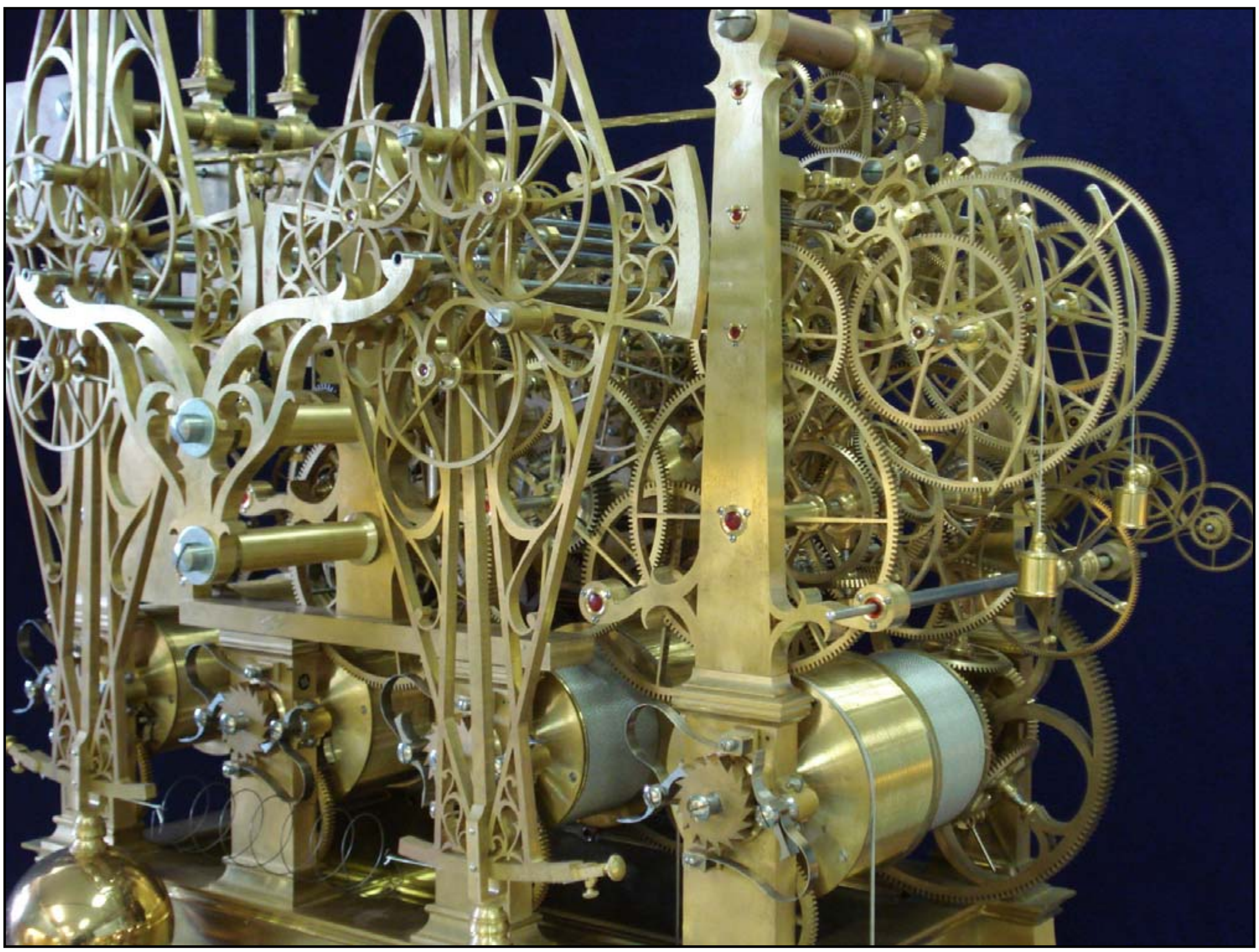


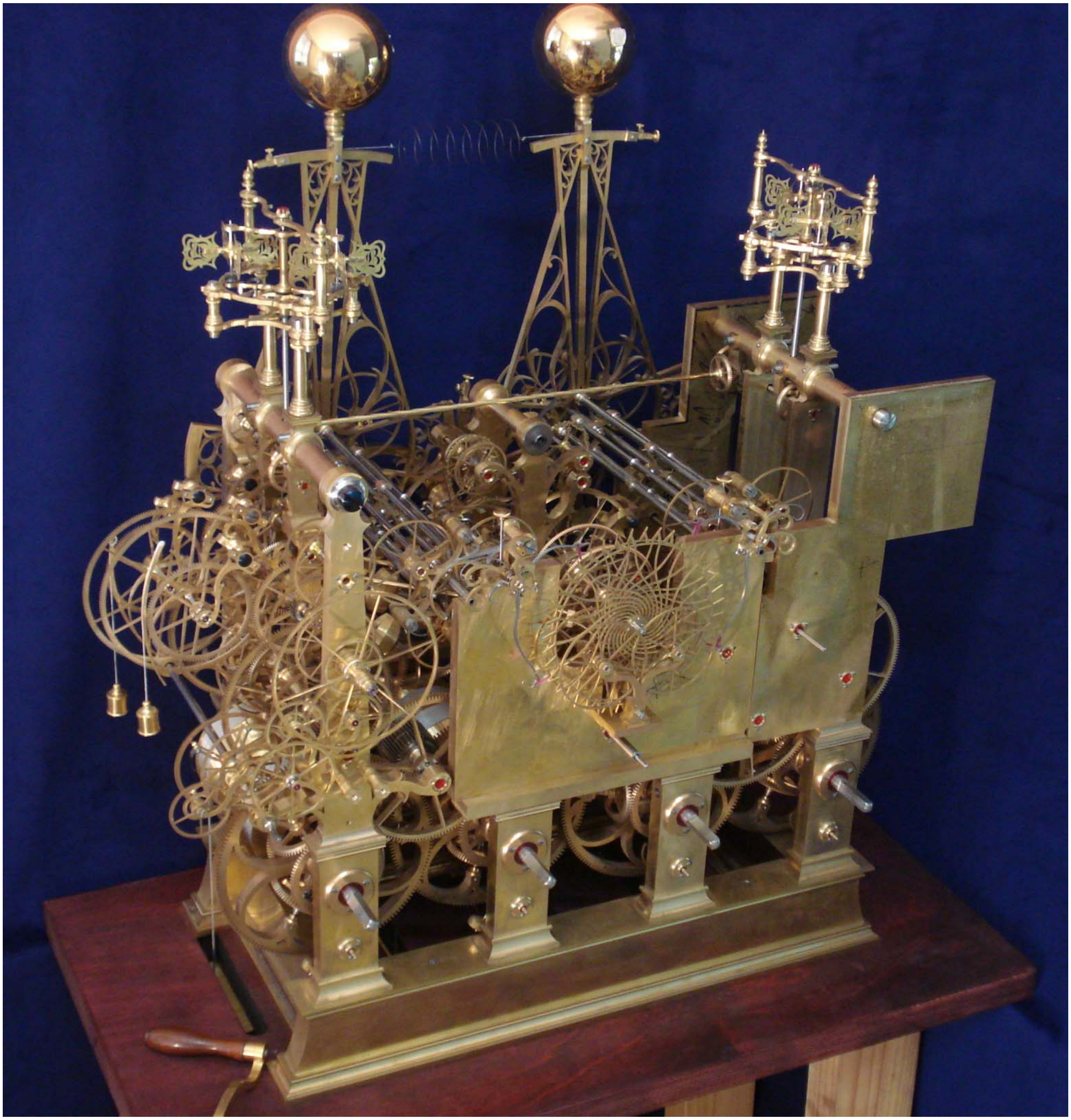
Figure 49. Time train frame allowing total viewing of wheels.

improvement compared to what a conventional plate would have offered (Figure 49). Figure 48 and 49 begin to show the philosophy behind the frame design. The architectural features of the pillars where the upper and lower frames meet adds a classic design touch in keeping with the entire lower frame's motif. This lower 'classical man-made structure' provides the foundation for, and morphs into, the organic forest of wheels held by the red jeweled fruit of the curvilinear trees above. In the open space just above the central trees will be the firmament in the form of an orrery. And what forest would be complete without animals? The escape pallets in the representation of four birds, Figure 21, page 9, continually forage in front of the forest as they peck away at the escapement wheels.

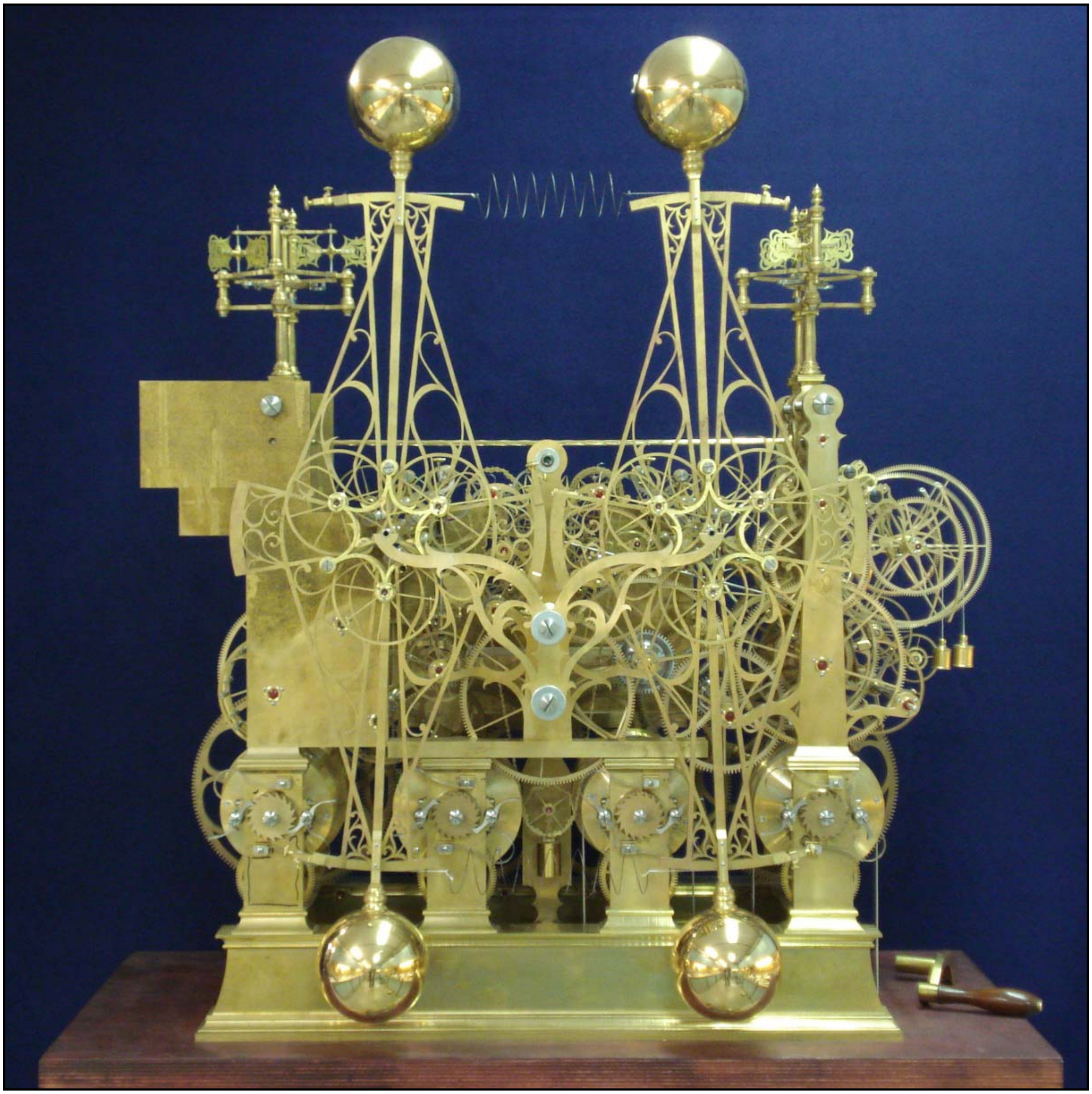
The remaining photos show where we are now after three years of work. We began this project with the four main wheels and then the time train. That train is complete and the clock has been running on and off for well over a year. We are working our way sequentially toward the right hand side comprising the celestial, quarter and hour strike trains. One can see this plainly in the progression of the plates and the wheels completed as we work our way rightward. Nearly all of the train works that belong between the plates are complete. Now begins the many celestial complications and all of the behind-the-dial-work. You can see several video clips of the clock functioning both when it was between the plastic frames last December as well as most recently this month after the transference to the metal frames at: http://www.youtube.com/user/fgtyc.

I hope this article conveys a bit of the effort, excitement and commitment that my partnership with Buchanan has in the creation of this clock, to you, the reader. I believe that we are making something very special that will stand the test of time as a horological artifact of significance. You can see the advancement of this project month by month at: http://www.my-time-machines.net/astro_index.htm. You may also email me through the website and comments, criticism or just plain conversation is always welcome.

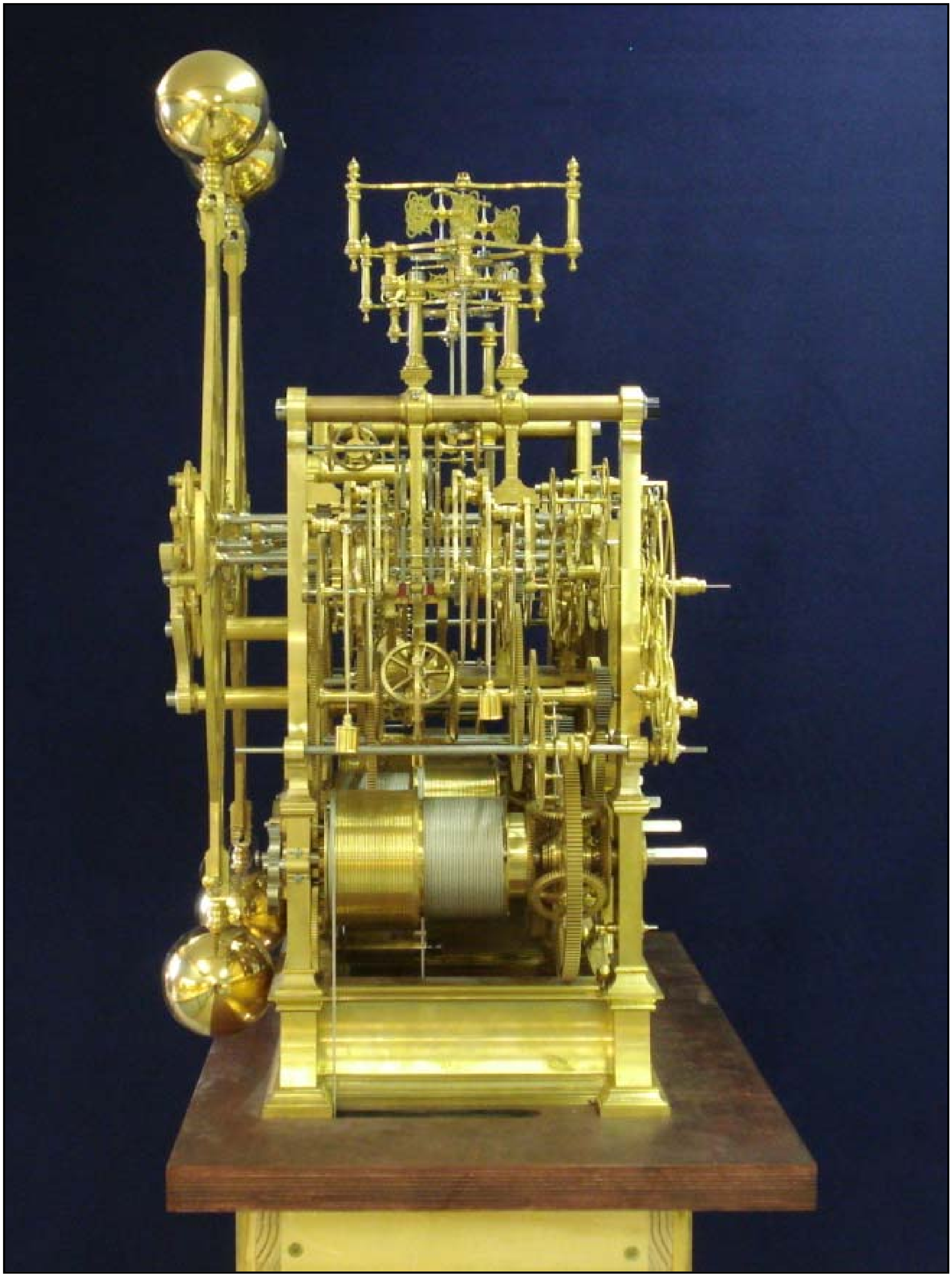




Three quarter, left-hand elevation. The front, center and right-hand (strike train) plates are yet to be cut to their final shapes. Overall dimensions are 26”w x 16”d x 32”h, or 57cm x 35cm x 70cm.



Rear elevation illustrating the intricate curvilinear designs of the dual pendulum balances and their support structure. The classically designed base serves as the man-made foundation for the organic forest of tree frames supporting the wheel works above. In the center space just above the pendulum support and in the space between the pendulum balances will be the orrery representing the heavens above the forest.



Left hand elevation showing a view through the time train and its remontoire. One of my early specifications was for Buchanan to construct the clock in such a way as to avoid the scene of a set of bare arbors spanning an empty space between the plates as seen end-on; as is the case in conventional movement design. This could have been done by varying the position of the wheels and pinions relative to each other to try to fill the space, but in the end this concern was obviated by the many wheels and complicated systems.

Footnotes:
1. Buchanan of Australia can be reached at: clocks@buchananesq.com.
2. The web site paper is at: http://www.my-time-machines.net/Astro_presentation_paper_final_web.pdf
3. For a brief discussion on remontoire: http://www.my-time-machines.net/remontoire.htm
4. For a biographical description of Rube Goldberg: http://en.wikipedia.org/wiki/Rube_Goldberg
5. To see John Harrison's famous H1 marine chronometer; which this movement shares some design similarities to: http://www.my-time-machines.net/halfwaypoint1
6. Die Planetenlaufuhr, Emmanuel Poulle, Helmut Sändig, http://www.my-time-machines.net/halfwaypoint2
7. Astronomische Uhren und Welt-Modelle der Priestermechaniker im 18 Jahrhundert, Antoine Simonin Verlang, Chapter 3.1 and 3.2, http://www.my-time-machines.net/halfwaypoint2
8. Geared to the Stars, Henry C. King, pp. 295-298, http://www.my-time-machines.net/halfwaypoint2
9. Spheres, J. Kugel, pp. 202-225, http://www.my-time-machines.net/halfwaypoint2
10. ANCHA, no. 43 May 1985, pp. 23-28, http://www.my-time-machines.net/halfwaypoint2
11. Jen Olsen's Clock, Otto Mortensen, pg 13, http://www.my-time-machines.net/halfwaypoint2
12. Masterpieces from the Time Museum, Sotheby's catalog December 2, 1999, pp. 58-77
13. Clockmaker Rasmus Sornes, The, Tor Sornes pg. 134, http://www.my-time-machines.net/halfwaypoint2
14. http://www.tuerler.ch/5en.html , http://www.my-time-machines.net/halfwaypoint2
15. Patrizzi & Co. auctioneers, April 25, 2010, lot # 311.
16. For a photo of this example, Smith of Clerkenwell: http://www.my-time-machines.net/smiths_musical_skeleton.htm
17. For a photo of this example, James Condliff: http://www.my-time-machines.net/condliff_detail.htm
18. For a photo of this example, Evans of Handsworth: http://www.my-time-machines.net/evans_arab1.htm
19. To see a stop-action video and audio presentation of the Wagner remontoire: http://www.my-time-machines.net/wagner_remontoir.htm
20. For a discussion on differentials: http://en.wikipedia.org/wiki/Differential_drive
21. For a description of the grasshopper escapement: http://en.wikipedia.org/wiki/Grasshopper_escapement
22. **Celestial complication count:**

1. Equation of time
2. Sidereal time

   400 year perpetual calendar:

3. Day
4. Date
5. Month
6. Year
7. Leap year indication
8. Sunrise/sunset horizon shutters
9. Sunrise/sunset time indication
10. Moonrise/moonset shutters
11. Moonrise/moonset time indication
12. Moon phase globe
13. Planisphere
14. With roving Sun showing travel through the Zodiac
15. Tellurium featuring the Earth, Moon and Sun system
16. Grand orrery, Mercury through Saturn, with Jupiter and Saturn each having five orbiting moons as known in the late 1700's

   Other complications:

17. Dual Wagner style gravity based swinging frame remontoire driving the escapements
18. Robin endless chain remontoire driving the celestial train with backup clutch
19. Power reserve indicator for each of four trains
20. Pull-repeat on demand for strike train
21. Compound fly fans, pirouette style for remontoire; Charles Fasoldt style epicyclical for strike trains

23. For a discussion of the Robin remontoire: http://www.my-time-machines.net/horz_2_train4.htm